Radar measurements of falling snow

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Ⅰ. INTRODUCTION

Many of us have spent winter days during our childhood playing in snow, skiing, sledding, throwing snowballs or making a snowman. On some occasions we could have caught a snowflake or two and studied their delicate beauty. Those picture perfect snowflakes are not a common place; they appear only in special conditions and never look the same. At those times we did not appreciate how complex is the problem of interpreting observations of snowfall, regardless of a technique one uses for observations.

At mid- to high- latitudes a significant part of winter precipitation falls in form of snow. Snow is also not unknown at lower latitudes, especially in the mountainous regions. For northern countries winter precipitation has a significant economic impact. It is estimated that in Finland, for example, winter road maintenance costs around 100 million Euros annually. This is a direct cost that does not include accidents, delays in logistics and working hour losses.

Snow is also a major part of a global energy and hydrological cycle. Due to phase transformations and accompanied energy exchange caused by life cycle of precipitation particles, precipitation is a major source of energy that drives atmospheric circulation. It is also a sink of atmospheric water. Not surprising that understanding of precipitation formation and life cycle is needed for accurate weather and climate predictions. Unfortunately, our current knowledge in this domain is rather incomplete. This is not in small part due to our inability of accurate quantitative winter precipitation estimation.

It is generally recognized, as can be seen from the planned and current satellite missions that microwave observations both passive and active provide the best quality precipitation estimates. One of the current problems that significantly affect precipitation estimates is the identification and retrieval of winter (frozen and mixed phase) precipitation. It arises from the fact that such regimes result in highly ambiguous microwave signatures for both active and passive instruments.

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Given my background, we will discuss here radar observations of falling snow and current challenges in this research field.

Ⅱ. WEATHER RADAR MEASUREMENT PRINCIPLE

Radar transmits and receives electromagnetic waves. The characteristics of the received signal, such signal power, phase, polarization and frequency, are used to infer information about objects that scattered the radio waves. In case of weather radars, observations depend on phase, size, shape, and density of precipitating particles. To infer physical properties of a cloud or precipitation, i.e. precipitation intensity, amount of water or ice contained in an observation volume, one needs to solve an inverse problem linking physical properties of the scattering media to the signal characteristics.

Because weather radars observe volume targets, the received signal power is inversely proportional to the square of the distance to a measurement volume and proportional to the sum of radar cross sections of raindrops or snowflakes located inside of this volume [1]:

$$P_r = \frac{c}{R^2}\sum_V \sigma_i \qquad (1)$$

Here c is the radar constant, and σ is a radar cross section (RCS) of a precipitation particle, and the summation is done over a unit volume.

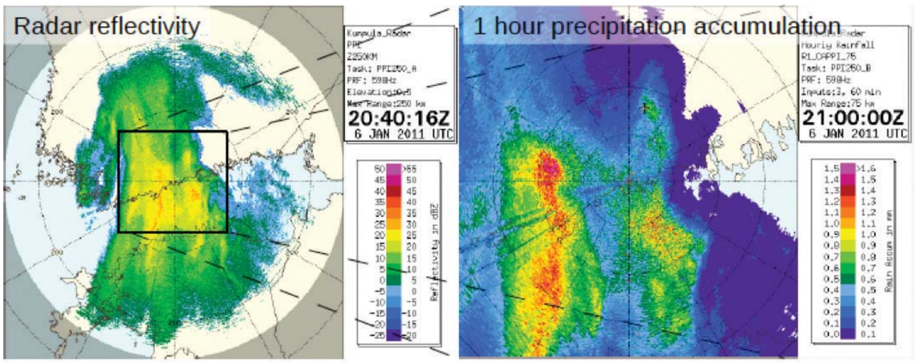
Typically, weather radars operate at wavelengths of 5 or 10 cm. At those wavelengths, scattering from most precipitation particles, or also know as hydrometeors, happen in the Rayleigh regime. In this regime, a RCS of a hydrometeor is defined as following:

$$\sigma = \frac{\pi^5 |K_p|^2}{\lambda^4} D^6 \qquad (2)$$

where $|K_p|^2$ is related to the complex refractive index of a hydrometeor [1]. For example for water it is 0.93 and for ice is 0.17.

To simplify interpretation of weather radar observations a new parameter, reflectivity factor, Z, was introduced

$$Z = \frac{\lambda^4}{\pi^5 |K_{water}|^2}\sum_V |K_{p,i}|^2 \sigma_i \qquad (3)$$



〈Figure 1〉 University of Helsinki radar observations of a snowstorm on Jan 6, 2011. On the left panel radar measurements at 20.40 UTC are shown. On the right figure one hour, 20.00 to 21.00 UTC, precipitation accumulation is presented

In case of rain, $|K_p|^2 = |K_{water}|^2$ and the reflectivity factor becomes $Z = \sum_V D_i^6$. This simplification shows the original purpose of this parameter. It was designed for rainfall measurements.By combining equations (3) and (1) one can see that the reflectivity factor and the received signal power can be easily related. So, when you next time see a weather radar image, such as one shown in 〈Fig. 1〉., there is a high chance that colors represent the reflectivity factor.

Snowflakes are particles that consist of a mixture of ice and air, therefore, $|K_p|^2$ is not equal to one of pure ice but should be calculated by using an effective medium approximation (EMA) [2], for example.

By using the Reyleigh scattering approximation and Maxwell Garnett EMA, one can express (3) in terms of physical properties of snowflakes as follows [1]:

$$Z = \frac{|K_{ice}|^2}{|K_{water}|^2} \sum_V \rho_{p,i}^2 D_i^6 \qquad (4),$$

where ρ_p is the density of a snowflake in the observation volume. Generally, snowflake density depends on a particle size, which is why it is inside of the summation.

The snowfall rate, expressed in terms of melted liquid equivalent, is defined as:

$$S = \frac{\pi}{6 \cdot \rho_{water}} \sum_V \rho_{p,i} D_i^3 v_i \qquad (5)$$

here v_i is the fall velocity of a snowflake.

Even a casual observation of equation (5) and (4) will indicate that there no unambiguous relation between Z and S. So, how do we use radar observations to estimate snowfall rate? The answer is the following. Based on observations we are establishing an empirical relation between reflectivity factor and snowfall rate. This relation is usually based on measurements carried our over a long period of time. For example, Finnish Meteorological Institute uses relation [3]; see 〈Fig. 1〉 for an example of its use.

how do we use radar observations to estimate snowfall rate?

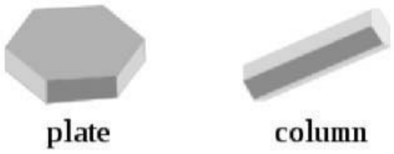
Equations (4) and (5) show that density of snowflakes is one of the factors that affect any Z-S relation. From our youth we remember that snowflakes can take different forms. Some of them hard and when they hit your face you can feel a sting. Some of them big and fluffy and slowly fall to the ground. This implies that density can change significantly from one snowstorm to another, and even within one snowfall event. That is why; it is not surprising that application of a single $Z=100 \cdot S^2$ relation could result in large errors.

Ⅲ. BRIEF INTRODUCTION TO SNOW MICROPHYSICS

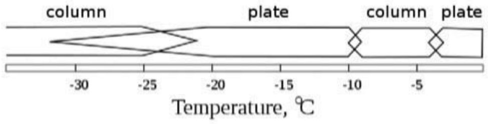
A. Ice crystal growth by water vapor deposition

Many of us heard an expression 'no two snowflakes are alike'. This expression gives an accurate impression that it is extremely difficult if not impossible to predict an exact shape of an ice crystal. We can, nonetheless, predict what type of particles will be formed given environmental conditions. Depending on temperature there are two principle growth modes of ice particles [5]. They can grow column like or plate like, see 〈Fig. 2〉. Which growth mode dominates depends on surrounding air temperature. This dependence is shown schematically in 〈Fig. 3〉. A careful reader can object, if this is so simple and so predictable why snowflakes are so different from each other. This is because the growth story is not complete yet. Surrounding air temperature only defines whether ice particles will grow column like of plate like. The amount of water vapor in the surrounding air defines the rest.

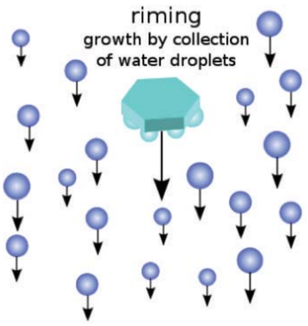
Ice crystals grow by water vapor deposition, where water molecules from the surrounding air condense on growing ice particle. The growth rate depends on the flux of the water molecules [4]. The larger the difference between an environmental water vapour pressure and a saturation vapor pressure above the ice particle surface, the higher the growth rate. This is similar to the flow of electrons in an electric field. From these simple considerations, we can infer that ice growth will be the fastest at parts of the particle that extend furthest from the rest of a particle. For a plate, corners of the hexagon would grow the fastest. Furthermore, this growth process will emphasize any imperfection in the shape, such a bump on the surface. Of course, this difference in growth of different parts of



〈Figure 2〉 Principle ice particle habits



〈Figure 3〉 Temperature behavior of principal ice habits growth, adopted from [5]



〈Figure 4〉 Schematic representation of an ice particle growing by riming particle will only be detectable in a strong water vapor field. Similarly, we only need to be worried about being hit by lightning during a thunderstorm. Therefore, the more water vapor is available the more delicate the resulting ice crystal will be. For example, the picture perfect, dendritic ice crystals grow at temperatures around −15 C in presence of supercooled water. The supercooled water acts as a source of water vapor.

B. Growth by riming

After ice crystals grew to an appreciable size, they can grow by collecting either supercooledwater droplets, if they are available, or by aggregating with surrounding ice crystals. Growth of ice particle by accretion of supercooled drops is often called riming. Particles that grew by riming are denser than any other snowflakes. It should be noted that ice particles do not always grow by riming in presence of supercooled water. It only happens if both ice particles and water droplets are large enough. If they are not large enough, then vapor deposition growth will dominate.

C. Growth by aggregation

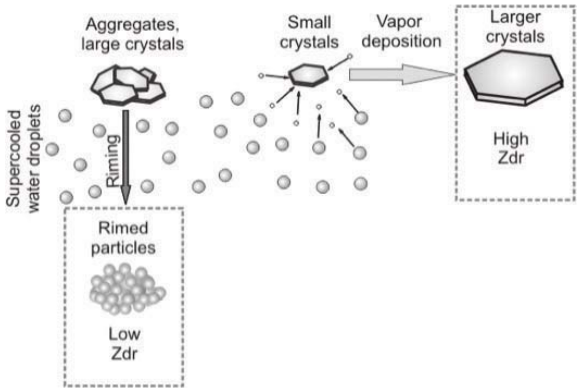
Growth by aggregation is more complicated than one by riming. Upon collision ice particle are not guaranteed to stay together. Probability of them staying together depends on their shape and air temperature. At temperatures close to 0 C, the probability of aggregation is the highest. This is due to a surface layer that is stickier at warmer temperatures. Also dendritic crystals are efficient in aggregation. This is due to their shape that is favoring interlocking of crystal branches. Aggregation results in large fluffy ice particles.

So if we are able to identify what growth process dominates, we should be able to choose a more appropriate Z-S relation.

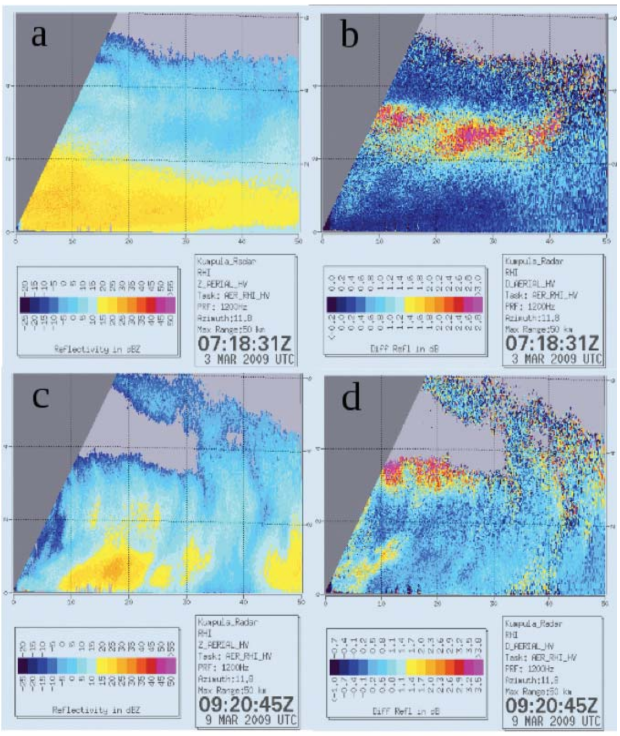
Ⅳ. IDENTIFICATION OF SNOW GROWTH PROCESSES

From the previous section we have learned that snow growth mechanisms define ice particle properties. For example, growth of ice crystals by water deposition in an environment that is rich in water vapor would result in delicate ice crystals. On the other hand, growth in a relatively poor in water vapor environment would result in denser particles. Riming would also result in dense particle, while aggregation would create large fluffy snowflakes. So if we are able to identify what growth process dominates, we should be able to choose a more appropriate Z-S relation.

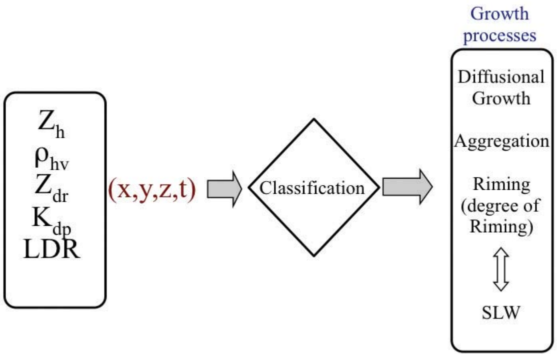
Before we start discussing how we can use radar observations to identify those processes, we need to introduce another radar measurable. Modern weather radar systems utilize dual-polarization radar technology; they can change polarization of the transmitted wave and measure two orthogonal components of a scattered wave. Typically, they employ linear horizontal and vertical polarizations. One can measure a ratio of received signal powers while transmitting and receiving h-polarization and the same for v-polarization. This ratio, called differential reflectivity or Z_{dr}, is related to the shape of hydrometeors [1]. Spherical particles will have low Z_{dr} values and oblate,



〈Figure 5〉 Depiction of a link between particle shape, snow growth mechanism and dual-polarization radar observations.



〈Figure 6〉 Examples of University of Helsinki radar observations of two snow storms. In the first event (a –b), an observer on the ground has reported large aggregates. In the second case (c–d) rimed aggregates were observed. Panels a and c show radar reflectivity and panels b and d present differential reflectivity for those events



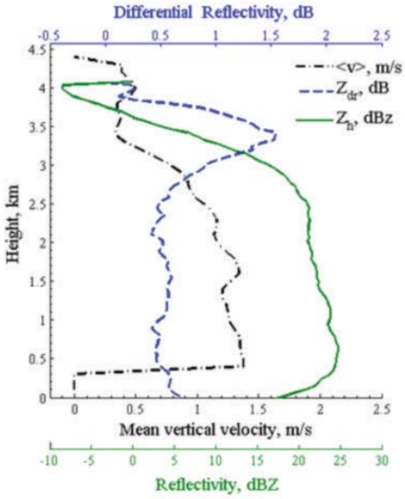
〈Figure 7〉 A simplified architecture of the dominating snow growth processes classification scheme

horizontally aligned particles will have larger Z_{dr} values. A relation between observed Z_{dr} and ice particles grown by different mechanisms are shown in 〈Fig. 5〉.

In 〈Fig. 6〉 observations of two snowstorm events are shown. We can see that both events exhibit similar reflectivity values and high Z_{dr} bands. An observer on the ground has reported that in one case, in the event that took place on March 3rd, 2009, snow particles falling on the ground were predominantly large snow aggregates. In the other case, the observer reported rimed aggregates at the time of the radar observations. So in both cases aggregation took place, only during the second event it was succeeded by riming.

By examining 〈Fig. 6〉, we can see that it is not sufficient to look at the radar observations on pixel-by-pixel basis. We should study the spatial behavior of radar observables. This approach is summarized in 〈Fig. 7〉.

So let us look at how aggregation process is observed by a dual-polarization radar. For this we will study a vertical profile of radar observations taken at a range of 32 km from the



〈Figure 8〉 Vertical profile of radar observations, taken on March 3rd, 2009

radar, where a vertically pointing Doppler radar was located.

Simultaneous Doppler and dual-polarization radar observations, presented in 〈Fig. 8〉. Observations presented in 〈Fig. 8〉 can be split into three regions starting from the echo top at about 4 km altitude and continuing to the ground.

The first region, located between 4 and 3.5 km above the ground, is characterized by a rapid growth of both Z_{dr} and Z_h. Differential reflectivity and reflectivity grow at rates of roughly 2 dB/km and 20 dBZ/km respectively. At the same time the mean Doppler velocity remains approximately constant and equal to 0.5 m/s.

The second region, located between 3.5 and 3 km above the ground, is characterized by a continuing rapid growth of reflectivity while differential reflectivity is rapidly decreasing. The differential reflectivity reached its maximum at the altitude of 3.5 km. At the same altitude the mean vertical velocity begin to increase, at a rate of more than 1 ms^{-1} / km, and reaches a value of about 1 m/s at 3 km above the ground.

The rapid growth of reflectivity and mean velocity ceases at about 3 km above the ground. From this altitude and to the ground, reflectivity increases at a rate of about 2.5 dBZ/km, mean velocity changes at a rate of 0.15 ms^{-1} / km and differential reflectivity stays more or less constant at a value of 0.5 dB.

The presented observations can be explained by a presence of two snow growth processes. The first stage of snow growth is characteristic of the vapor deposition crystal growth. Growth of these particles explains increase in Z_{dr} and initial increase in reflectivity. At the later stage, aggregation of these particles starts to play more and more important role, which explains further increase in reflectivity and rapid change in the observed fall velocity. At the last stage, aggregation dominates the growth process.

It appears to be, though more study is needed, that this kind of vertical profile is characteristic of an aggregation dominated snowflake growth. It should be noted a similar profilescouldalso be seen in observations of March 9th, 2009 event. This is inline with the surface observations, which reported aggregates in both cases. In [6] it was reported that those signatures could be also associated with a rapid change in visibility.

One also can see that the reflectivity field in March 3rd case is more continuous than the one in March 9th case. Whether this difference is associated with riming is a topic of a future study [7].

V. CONCLUSION

In this paper we have went from the

introduction of weather radar observations to how they relate to precipitation microphysical properties. We have discussed current challenges in the weather radar observations of winter precipitation. A new concept, identification of dominating snow growth mechanisms, was introduced and illustrated by using University of Helsinki radar observations. The story is not complete, there are still many opportunities for future research left.

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〈관심 분야〉
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